Neutrino factory and beta beam: accelerator options for future neutrino experiments

Michael S. Zisman[1]

[a] *Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, U.S.A.*

Abstract

Two accelerator options for producing intense neutrino beams—a Neutrino Factory based on stored muon beams and a Beta Beam facility based on stored beams of beta unstable ions—are described. Technical challenges for each are described and current R&D efforts aimed at mitigating these challenges are indicated. Progress is being made in the design of both types of facility, each of which would extend the state-of-the-art in accelerator science.

Keywords: Neutrino Factory; Beta Beam; intense neutrino source

1. Introduction

The discovery of neutrino oscillations has motivated substantial accelerator R&D and design efforts aimed at providing intense beams of accelerator-produced neutrinos. A number of concepts for producing the requisite beams have been proposed, including:

- a Superbeam facility based on decays of an intense pion beam
- a Beta Beam facility based on the decays of stored beams of beta-unstable ions
- a Neutrino Factory based on the decays of stored muon beams

The last concept, the Neutrino Factory, has the advantage of being a possible precursor to a future Muon Collider.

All of the above approaches are challenging, and it is likely that all will be expensive. The EUROnu program [1] is currently completing a comparative review of the capabilities and costs for all three types of facility. Here, we will focus only on the last two options, the Beta Beam and Neutrino Factory.

2. Physics Context

A Beta Beam facility provides only electron neutrinos. The baseline scenario [2] makes use of ^{6}He β^{-} decays to produce electron anti-neutrinos and ^{18}Ne β^{+} decays to provide electron neutrinos. This scenario produces low energy neutrinos. An alternative scenario making use of ^{8}Li and ^{8}B, isotopes having higher decay *Q*-values, gives higher energy neutrinos but suffers from difficulties in preparing the isotopes in the required quantities.

A Neutrino Factory provides both electron and muon neutrinos. Negative muon decays result in an equal mixture of electron anti-neutrinos and muon neutrinos, and positive muon decays give an equal mixture of electron neutrinos and muon anti-neutrinos.

Electron neutrinos and anti-neutrinos are most favorable for doing the science, as these give rise to easily detectable “wrong-sign” muons; these are not usefully produced with a “conventional” neutrino beam, such as produced at a Superbeam facility.

[1] Corresponding author. Tel.:+1-510-486-5765; fax +1-510-486-5788; e-mail: mszisman@lbl.gov.

3. Physics Reach

There are two main thrusts of the physics program at the neutrino facilities considered here:

- determination of the mass hierarchy
- discovery, and subsequent investigation, of CP violation in the lepton sector

In view of the recent measurements [3, 4] indicating that $\sin^2 2\theta_{13}$ is relatively large, it appears (see Fig. 1) that most proposed experiments can determine the mass hierarchy, so this capability no longer distinguishes the different options.

For CP violation studies, however, the performances of the various facilities are not the same. As can be seen in Fig. 2, the Neutrino Factory has the best physics reach for CP violation. The combination of a Superbeam and Beta Beam is nearly competitive with the Neutrino Factory, though it requires two separate projects to be constructed. For the measured value of $\sin^2 2\theta_{13}$, control of systematic errors will be critical to the success of CP violation determinations; at present, widely different assumptions have been made for these errors—a situation that must be improved.

The precision of CP violation measurements is directly related to constraints on the unitarity triangle, which, in turn, are most sensitive to the influence of "new physics." In the end, the sensitivity to new physics will depend strongly on the ability to control systematic errors. A preliminary indication of systematics effects is shown in Fig. 3, from Coloma et al. [5], which includes the effects of both near and far detectors. Only the Neutrino Factory is capable of the level of precision reached in CKM matrix studies and is not dominated by systematic errors. Indeed, even at a markedly reduced intensity, the Neutrino Factory is competitive with alternative approaches.

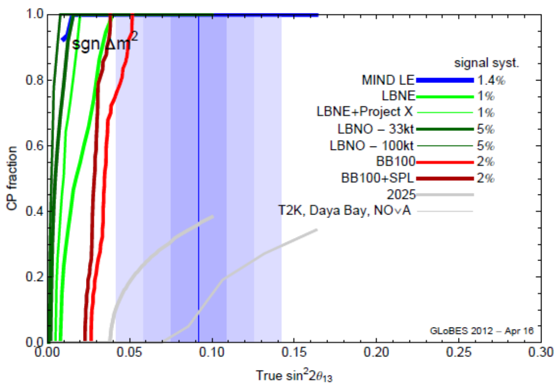

Fig. 1. Mass hierarchy coverage of various proposed projects for a range of $\sin^2 2\theta_{13}$ values. The shaded region indicates the measured value of $\sin^2 2\theta_{13}$ with 1σ, 2σ and 3σ errors indicated.

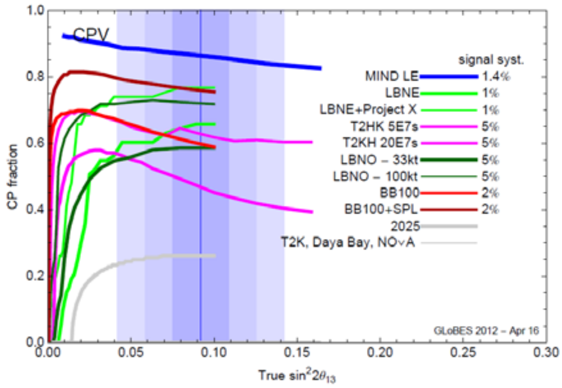

Fig. 2. CP violation coverage of various proposed projects for a range of $\sin^2 2\theta_{13}$ values. The shaded region indicates the measured value of $\sin^2 2\theta_{13}$ with 1σ, 2σ and 3σ errors indicated.

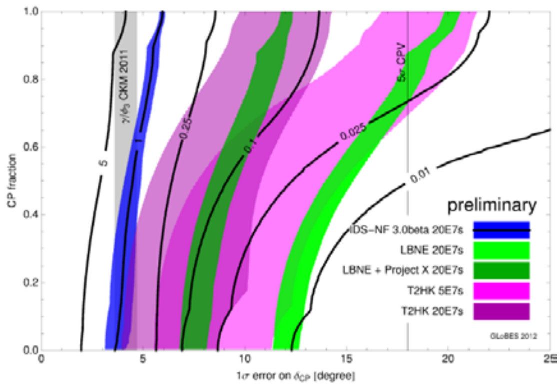

Fig. 3. Impact of systematics on the performance of various projects. The left side of each band represents no systematic errors and the right side shows full systematic errors. The solid lines represent Neutrino Factory performance for the indicated intensity, where 1 represents the nominal value of 10^{21} neutrino decays per year.

4. Beta Beam Description

The baseline Beta Beam facility is shown in Fig. 4. It consists of a proton driver based on Linac4 at CERN, an ISOL or molten-salt target, a pulsed Electron Cyclotron Resonance (ECR) ion source, an acceleration system comprising a linac, a rapid-cycling synchrotron, the CERN PS and the CERN SPS rings, and a decay ring of 6.9 km circumference with straight sections of 2.5 km length.

Two concepts are being explored: a low-Q version based on decays of ^{6}He and ^{18}Ne beams, and a high-Q version based on decays of ^{8}Li and ^{8}B beams.

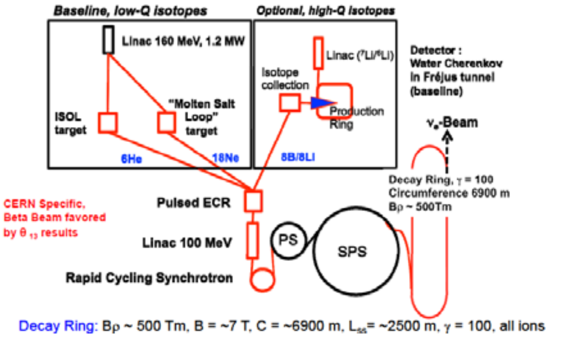

Fig. 4. Schematic layout of Beta Beam facility on CERN site. Both the low-*Q* baseline and high-*Q* optional design are indicated.

5. Neutrino Factory Description

The Neutrino Factory, shown in Fig. 5, comprises many sections. A proton driver provides a primary beam to a production target where pions are created that decay to muons. The muon beam is bunched and rotated in longitudinal phase space to reduce its energy spread. The beam emittance is then reduced by passage through an ionization cooling channel. Thereafter, the beam is accelerated from about 130 MeV to 10 GeV using a linac, a recirculating linear accelerator, and a fixed-field, alternating gradient (FFAG) ring. Finally, the beam is stored for about 1,000 turns in a decay ring with a long straight section aimed at a detector some 2,000 km away.

One noteworthy aspect of the Neutrino Factory is that it can be staged. The νSTORM concept illustrated in Fig. 6 could serve as a "starter facility," that is, the first step along a path toward a full Neutrino Factory. The idea is to use an existing 60 GeV proton beam at Fermilab to produce muons of about 4 GeV. The facility would use a solid target capable of handling 10^{21} protons on target over 5 years of operation. The muon beam would be selected with magnetic horns, or possibly a Li lens, and transported to a storage ring. The neutrinos from the decay ring (2×10^{18} during 5 years of operation) would illuminate a far detector located ~2 km from the ring for doing short-baseline oscillation physics. The near detector, located close to the ring, would serve for precision electron neutrino and anti-neutrino cross section measurements, of value to all future neutrino experiments. A letter of intent for such an experiment has been submitted [6] to the Fermilab scientific program committee. Note that all components of the facility are standard devices requiring no development, so construction could begin immediately after approval.

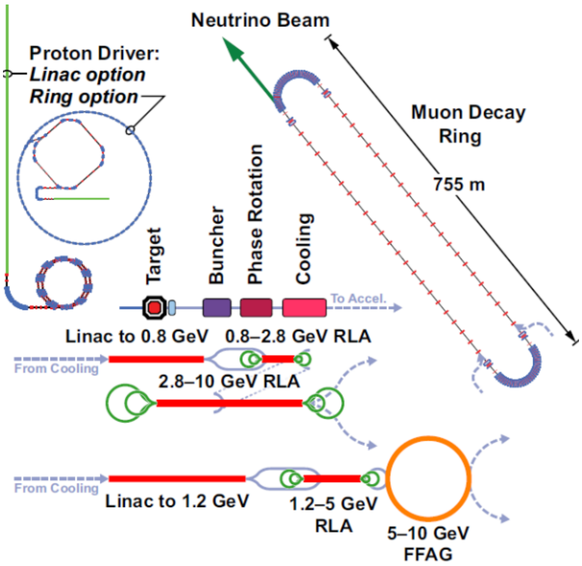

Fig. 5 Schematic of baseline Neutrino Factory layout from IDS-NF study.

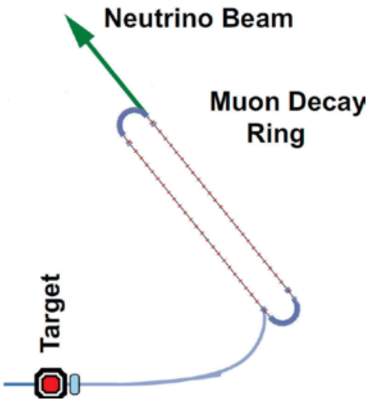

Fig. 6. Schematic layout of proposed νSTORM facility at Fermilab.

There is another possible stage in the sequence of stored muon facilities—a Muon Collider. This could initially be a Higgs factory to study the newly discovered Higgs candidate particle, and ultimately an energy frontier collider at a center-of-mass energy of 3 or 4 TeV. Because the front-end designs for the Neutrino Factory and Muon Collider are similar, the Neutrino Factory R&D effort in large measure serves both designs. However, the Muon Collider requires considerably more cooling than does the Neutrino Factory (not only transverse cooling but also longitudinal).

6. Beta Beam Technical Challenges

For the Beta Beam, the main technical challenge is production of the required ion species with adequate intensities. "Production" here includes not only creating the ions but collecting them, transporting them to an ion source, ionizing them, and bunching them suitably for downstream acceleration.

6.1. Ion Production

Production has been studied for both ^{6}He and ^{18}Ne. For the former ion species, obtaining adequate intensity appears not to be a problem. For the latter ion species, the preferred approach is to use the ^{19}F(p,2n) reaction. To handle the required proton beam intensity, the plan (see Fig. 7) is to use a NaF:LiF eutectic as a molten-salt target. The expectation is that a 1 MW proton beam will provide 9×10^{12} ^{18}Ne ions, which is close to the required intensity. However, this production rate remains to be demonstrated experimentally. Initial test experiments have recently begun at the CERN-ISOLDE facility.

6.2. Collective Effects

A second technical issue for producing a Beta Beam is that of collective effects. In order to mitigate backgrounds, the beam must be highly bunched, that is, the single-bunch intensity is high. Design parameters call for a bunch intensity of 3×10^{12} particles in a 5 ns bunch. Present estimates indicate that the transverse mode-coupling instability will limit the beam intensity in the Beta Beam decay ring. Optics changes have subsequently been made to the decay ring to reduce the transition gamma from 27 to 18, which mitigates the instability.

Although in earlier designs a duty factor of 0.5% was assumed to be necessary, the recently measured [3, 4] value of $\sin^2 2\theta_{13}$ should permit an increase to 2%, thus easing beam stability limitations. Nonetheless, it presently appears that the beam required in the SPS would be unstable. Because the SPS has other ongoing uses, the option of changing the lattice to mitigate instability problems is unavailable.

In both the PS and SPS, the beam must cross transition during the acceleration cycle. Especially for intense bunches, this typically leads to beam loss. Schemes for transition crossing for bunches of the design intensity need to be studied.

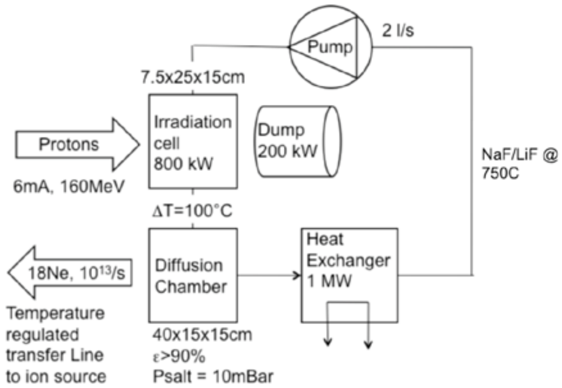

Fig. 7. Schematic of the molten-salt production loop for ^{18}Ne. Tests of the scheme are being done at CERN.

7. Neutrino Factory Technical Challenges

The technical challenges of a muon beam facility are associated with features of the muons. Firstly, the muons are produced as a tertiary beam (that is, protons interact with the target to give pions, which subsequently decay to muons). This means that the production rate is low, requiring a target that can handle multi-MW of beam power, and that the beam is created with a large energy spread and large transverse phase space, requiring some form of emittance reduction ("cooling") along with high acceptance acceleration systems and decay ring.

Secondly, muons have a lifetime of only 2.2 μs at rest. Such a short lifetime puts a premium on rapid beam manipulations, and leads to the need for high-gradient rf cavities, the presently untested technique of ionization cooling, and a rapid acceleration system.

7.1. RF Issues

A muon cooling channel requires high-gradient rf cavities to operate in an axial magnetic field. Initial experiments with this configuration [7] showed degradation of the maximum gradient due to the field. This is believed to be associated with the input coupler, but the matter is presently unresolved. An alternative approach using a high-pressure insulating gas has been shown to eliminate the magnetic field effect [8] and tests with beam are under way. Initial results [9] are encouraging. As indicated in Fig. 8, the beam causes severe beam loading but there is no evidence for breakdown.

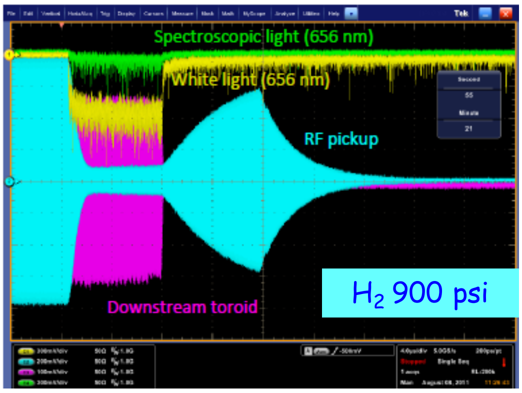

Fig. 8. Scope traces of gas-filled cavity performance with beam. Cavity rf signal is in cyan, beam pickup is in magenta.

A new 805-MHz cavity designed for Muons, Inc. to operate either with vacuum or with high-pressure gas has recently been fabricated. Initial tests at the Fermilab MuCool Test Area (see Fig. 9) showed no degradation in gradient under vacuum conditions. This is an encouraging result, but needs to be better understood. If verified, this result would indicate that the previously observed degradation is not a fundamental problem.

8. R&D Activities

To transform the challenges described above into opportunities, worldwide R&D efforts are under way. Of most interest are the efforts of the EUROnu study [1] and the IDS-NF [10]. For the Beta Beam, the main R&D topics are ion production, collective effects, and beam loss issues. For the Neutrino Factory, high-power target design, ionization cooling, and rf studies are the main activities.

Fig. 9. New 805-MHz cavity installed in 5 T solenoid in the Fermilab MuCool Test Area.

8.1. Beta Beam

Studies are under way to measure the production cross sections for the isotopes of interest, ^{18}Ne (see Sec. 6.1), ^{8}Li, and ^{8}B. The original concept for producing ^{8}Li and ^{8}B was to use reverse kinematics. Unfortunately, this was found to be impractical, because the required gas-jet target thickness was several orders of magnitude beyond manageable values. Present investigations focus on ^{7}Li(d,p)^{8}Li and ^{6}Li(^{3}He,n)^{8}B reactions. Cross sections have been measured at 6 MeV, but 25 MeV data are needed.

Another area of R&D is on development of a 60 GHz ECR ion source, as shown in Fig. 10.

8.2. Neutrino Factory

Progress is being made in adding engineering realism to the target area design. The target area magnet designs now have additional space between them to facilitate repair and the target magnet support structure has been designed.

Beam loss in the front end of the machine has been identified as a major challenge. To avoid protons being lost further downstream, a chicane and proton absorber have now been added to the transport system, as shown in Fig. 11.

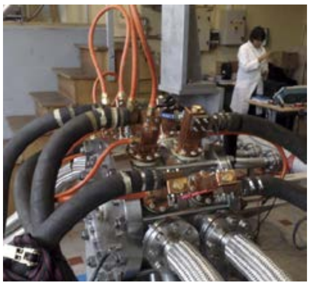

Fig. 10. 60 GHz ECR source under development at Grenoble.

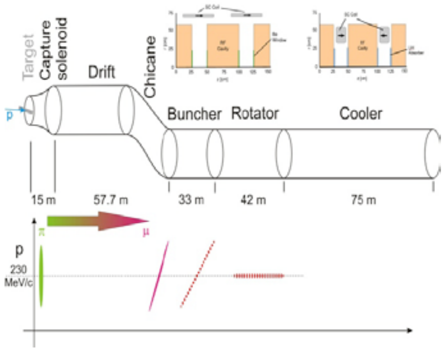

Fig. 11. Schematic of updated Neutrino Factory front end layout showing chicane.

Studies for the acceleration system include testing of EMMA, an electron model of an FFAG ring, at Daresbury Laboratory (see Fig. 12). The aim of this program is to study the accelerator physics of a non-scaling FFAG, including investigations of longitudinal dynamics, transmission, emittance growth, and the influence of resonances.

The main emphasis of the Neutrino Factory R&D program continues to be the Muon Ionization Cooling Experiment (MICE), sited at Rutherford Appleton Laboratory (RAL). MICE (Fig. 13) will test one cell of the Feasibility Study 2 [11] cooling channel, comprising three focus coil modules with absorbers (either liquid hydrogen or solid), and two RF-Coupling Coil modules, each with four RF cavities and a large-diameter superconducting coupling coil. At the upstream and downstream ends of the channel there is a superconducting solenoid magnet containing a scintillating fiber tracking detector that serves to measure the incoming and outgoing particle parameters for emittance determination. Other detectors measure time-of-flight and identify particle type.

The MICE beam line has been commissioned [12]. Civil engineering for MICE is nearly completed (Fig. 14), with the exception of the RF power supply

Fig. 12. Photograph of 16.6 m circumference EMMA ring at Daresbury Laboratory.

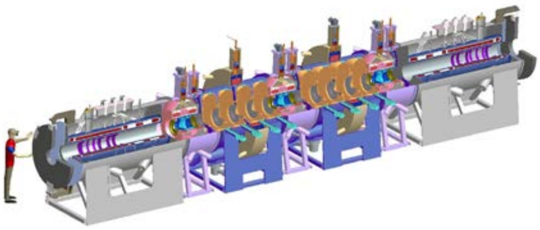

Fig. 13. Diagram of MICE experiment at RAL.

Fig. 14. View of the MICE experimental area looking upstream with the beam dump in the foreground.

installation. Cooling channel components are currently being fabricated and will be installed in the MICE hall when ready.

9. Summary

As outlined in this paper, substantial progress is being made toward the designs of accelerator-based neutrino facilities to study CP violation in the lepton sector. The technical challenges to be faced are being identified, understood, and overcome. The work outlined here on high-power targets, innovative cooling techniques, ion source development, and rapid acceleration techniques is extending the state-of-the-art in accelerator science and technology.

In order to see one or more of these projects come to fruition, it will be important for the community to decide the direction it wishes to proceed in. It is unlikely that the goal will be achievable in a single step, but having a clear destination in mind will at least avoid taking lengthy and expensive detours.

Acknowledgments

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